

REPORT DOCUMENTATION PAGE			Form Approved OMB No. 0704-0188	
<small>Public Reporting Burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing the burden, to Washington Headquarters Service, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.</small>				
1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE 1 Sept, 1996	3. PERFORMING ORGANIZATION NAME(S) AND DATE(S) COVERED <del>CONFIDENTIAL</del> , 01 June 95 to 31 July 96		
4. TITLE AND SUBTITLE Non-Invasive, Photochromic-Tracer Studies of Particulate Suspensions and Granular Media		5. FUNDING NUMBERS AFOSR F49620-92-J-0037		
6. AUTHOR(S) J.D. Goddard, P.I.		AFOSR-TR-96		
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) University of California, San Diego Applied Mechanics and Engineering Sciences-4011 9500 Gilman Drive La Jolla, CA 92093-0411		0501		
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) AFOSR/FA Boiling and Phase Change 0501-0411		10. SPONSORING/MONITORING AGENCY REPORT NUMBER NA F49620- 92-J-0037		
11. SUPPLEMENTARY NOTES The view, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy, or decision, unless so designated by other documentation.				
12a. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution unlimited.		12b. DISTRIBUTION CODE		
13. ABSTRACT (Maximum 200 words)  The subject research is being carried out by the research group of the P.I., including the efforts of a Postdoctoral Research Engineer, Dr. Florence Cantelaube, who recently received her Ph.D. in Physics from the University of Rennes, France, and an undergraduate Laboratory Assistant, Mr. Ben King, a Senior majoring in Chemical Engineering, at UCSD. Both are supported by grants other than the subject AASERT award.  Efforts are being made to identify an AASERT Graduate Fellow during the upcoming academic year 1996-97. We have achieved almost perfectly transparent dispersions of photochromic glass particles in ZnCl solutions are currently developing optics to focus a UV beam in the dispersion. Also, efforts are being made to dope polymeric beads with an organic (pyrospyrans) dye.				
14. SUBJECT TERMS Non-Invasive, Photochromic-tracer, Particulate Suspensions and Granular Media		15. NUMBER OF PAGES 6		
		16. PRICE CODE		
17. SECURITY CLASSIFICATION OF REPORT UNCLASSIFIED	18. SECURITY CLASSIFICATION UNCLASSIFIED	19. SECURITY CLASSIFICATION OF ABSTRACT UNCLASSIFIED	20. LIMITATION OF ABSTRACT UL	

19961016 146

Final Technical Report  
for the period  
01 October 1992 to 30 June 1995  
on  
AFOSR Research Grant F49620-92-J-0037

Mechanics, Transport Properties and Statistical Physics  
of Granular Media and Geomaterials

Submitted  
to

ATTN: Maj Conrad Felice  
Air Force Office of Scientific Research (AFMC)  
AFOSR/NA  
Duncan Ave., Ste. B115  
Bolling AFB, DC 20332-0001

by

J.D. Goddard  
Principal Investigator  
Department of Applied Mechanics and Engineering Sciences  
University of California, San Diego  
La Jolla, CA 92093-0411

30 September 1995

## SUMMARY

This is a summary of research performed under the subject AFOSR grant on the micromechanics, continuum mechanics and transport properties of granular media and geomaterials. It has involved the development of new theoretical models of microstructure, numerical simulation of granular assemblages, and experimental observation on model systems. The overall goal of the work is to provide a sound microstructural basis for understanding continuum behavior and elucidating structurally and geologically important phenomena such as the propagation of acoustic and seismic waves, the quasi-static yield of granular media, the structural stability of soils and their liquefaction, and the non-invasive testing of geomaterials.

The three and one half year effort has involved the Principal Investigator, a postdoctoral research associate, one Ph.D. research assistant and various M.S. research assistants supported in part by the AFOSR grant. This has involved the development and application of an improved computer simulation for idealized granular assemblages to the prediction of dilatancy, scalar conductivity and yield surfaces, continuing development of experimental methods for granular media, and the inception of related work on continuum-mechanical mixture theories for fluid-particle systems and porous media.

## RESEARCH ACTIVITY AND OBJECTIVES

The specific research activities and goals of the research are summarized here:

### (1) Micromechanical Analysis of Granular Media and Geomaterials

The research has involved a continuing effort to apply various analytical methods, such as discrete-element and network representations, together with standard homogenization techniques, such as effective-medium or self-consistent techniques, to infer continuum response from microstructure and micromechanics. The goal is understanding and modelling of the quasi-static mechanical response and transport properties of granular media and fractured or jointed geomaterials.

### (2) Large-scale Numerical Simulations of the Quasi-Static Mechanics of Granular Assemblages

This effort is aimed at applications of a computational method developed earlier in this research program. A major objective is to investigate the effects of evolving particle-contact topology on dilatancy and on other mechanical and transport properties in frictional-elastic particle assemblages. A related goal is to simulate the plastic response of such assemblages in complex loading paths, as a guide to the development of continuum plasticity theory for granular media and geomaterials.

### (3) Development of Experimental Methods

Part of the current effort has involved the development and application of a novel test cell for conductive granular materials which allows one to monitor stress and electrical conductivity simultaneously. Also, as part of an effort launched under a companion AFOSR AASERT Fellowship award, we have worked on the development of transparent, refractive-index matched fluid-particle dispersions with UV-excitable photochromic-dye doped particles, to permit non-invasive study of the kinematics in fully 3D granular assemblages and particulate suspensions.

## ACCOMPLISHMENTS AND PROGRESS

### **Research Accomplishments**

Following is a summary of the major research accomplishments to date, together with a listing of publications, related activities and personnel:

### (1) Numerical Simulation and Theoretical Analysis of Reynolds Dilatancy and Plastic Yielding in Idealized Granular Assemblages

A new method has been developed for the computer simulation of the quasi-static mechanics and conductivity of frictional-elastic sphere assemblages, the subject of several reports, conference presentations and publications cited below [J2,C2,C3,R1,R2,T1,T4,T11]. As discussed there, the simulations show quite good agreement with experiments on an idealized granular medium consisting of a stainless steel ball bearing assemblage. As a recent effort over the past few months, the above computer simulation has been applied to the calculation of yield surface evolution for assemblages of rigid frictional spheres subject to elementary proportional loading histories, including uniaxial compression, pure shear (planar uniaxial compression), and equi-biaxial compression (uniaxial extension), as well as simple shear. We have investigated the effects of initial density (void ratio), polydispersity (unequal sphere sizes), intergranular friction and total plastic strain. Remarkably, the simulations indicate an asymptotic approach to the empirical Lade-Duncan yield surface of soil-mechanics at plastic strains of only a few (ca. 5) percent. Also, it is found [T12, T13] that the purely theoretical kinematic estimate of dilatancy based on a network model proposed by one of us [C1, T2,T3] for the limit of zero friction provides a reasonable upper bound for the uniaxial strength of frictionless, monodisperse assemblages. In a publication now in preparation [J5], we show how these findings may point the way to a rational, semi-theoretical predictive scheme for the plastic yield strength of granular media, based on relatively simple modifications of the classical Rowe stress-dilatancy model for rigid particle assemblages.

### (2) Development of Experimental Methods

A small triaxial cell, with provision for stress and electrical conductivity measurement as well as for pore liquid monitoring and control was developed. This cell has been employed in the studies discussed above on steel ball assemblages without liquid. With a view towards future studies of conductive granular material, a low-cost commercial source has been identified for low-cost, extremely hard metallic spheres, which may not be as susceptible to plastic yielding at the contact points as the steel balls employed in our current research [J2,R1,R2].

Progress on the development of the photochromic tracer technique has been somewhat sporadic. We have been able to synthesize a kind of "photochromic sand" by crushing photochromic glass (provided by the Corning Company), of the type which darkens on exposure to W (as in sunglasses, automotive sunscreens, etc.), but the darkening is rapid and impedes deep penetration of the excitation UV beam. Also, initial attempts to impregnate commercially available acrylic beads with an organic photochromic dye (a spiropyran) have not been successful, suggesting that synthesis of dye-containing beads may be necessary. At present, the P.I. is recruiting a highly qualified Ph. D. candidate to continue the work under a companion AFOSR AASERT fellowship grant.

### (3) Related Studies on Fluid-Particle Systems

As independent but related research, Dr. Didwania has carried out theoretical studies of fluid-particle suspensions [J3,J4]. Also, Professor Reint de Boer, from the University of Essen, Civil Engineering, supported by the German VW Stiftung in the period September 1994-March 1995, worked with us on the foundations of continuum mixture theory with a view towards application to two-phase particle-fluid systems, including porous media, fluid-saturated granular media and fluidized particulate beds.

### **Personnel**

#### Supported in part by grant:

J.D. Goddard, Principal Investigator (1991-)  
X. Zhuang, Ph.D. Graduate Research Assistant (1991-; Ph.D. completed in 1993)  
A.K. Didwania, Research Scientist/Scholar (1992-)  
Laura Nett, Graduate Research Asst. and AFOSR AASERT Fellow (Summer 1993)  
Maria Guevara, Graduate Research Asst. and AFOSR AASERT Fellow (Fall 1993)

#### Other:

Pejman Fani, M.S. Independent-Study Student, (1993-94; M.S. completed 1995)  
Monica Orski, Graduate Independent-Study Student (1994; French Diplome d'Etudes Avancees completed 1994)  
Reint de Boer, Prof. Civil Eng., U. of Essen, Visiting VW Stiftung Research Scholar (9/94-3/95)

## **Publications\***

### Refereed Journals

#### *Completed:*

- J1. Goddard, J.D. "A note on path-dependent strain measures and strain jumps in isotropic simple materials", J. Non-Newtonian Fluid Mech. 54, 195-199 (1994).\*
- J2. Zhuang, X., Didwania, A.K., and Goddard, J.D., "Simulation of the Quasi-Static Mechanics and Transport Properties of Granular Materials", in the press, J. Computational Phys. 121, 16pp., October (1995).
- J3. Didwania, A.K. and Sangani, A.S., "Magnetic field stabilization and dispersed-phase pressure of bubbly ferro-fluids at high Reynolds number", accepted and to appear, European J. Mech. B/Fluids, 1995.\*
- J4. Didwania, A.K., "New Beltrami type solutions to the continuum equations for fluidization and their stability", Physica D 84,532-544 (1995).\*

#### *In Preparation:*

- J5. Goddard, J.D., Didwania, A.K. and Zhuang, X., "Numerical Simulations and Theoretical Estimates of the Reynolds Dilatancy and Yield Surfaces of Granular Assemblages", in preparation for submission, 1995.

### Conference Proceedings and Book Chapters

- C1. Goddard, J.D., "New Theoretical Estimates for Reynolds Dilatancy in Granular Media" in Moldenaers, P. and Keunings, R.(eds.)Theoretical and Applied Rheology, Proceedings 11th International Congress on Rheology, Brussels, Belgium, 17-21 August 1992., Vol. I, pp. 141-142, Elsevier, 1992.
- C2. Goddard, J.D., Didwania, A.K. and Zhuang, X. "Computer simulation and experiment on the quasi-static mechanics and transport properties of granular materials", in Guazzelli, E. and Oger, L. (eds.) "Mobile Particulate Systems" ( Proceedings of a N.A.T.O. Advanced Study Institute, Cargese, Corsica, 4-16 July 1994) Kluwer,1995.
- C3. Videocassette and accompanying text: "Numerical Simulation of the Micromechanics of Granular Assemblages", in Video Anthology , "Rheology in Motion", presented at the 65th Ann. Society of Rheology Meeting, Boston, MA, (ed. G. McKinley, Harvard University, School of Applied Science, Cambridge, MA, 1993. (Copies available from the Editor)

### Dissertations and Reports

- R1. Zhuang, Xuejin 1993 "Computer Simulation and Experiments on the Quasi-Static Mechanics and Transport Properties of Granular Media" Ph.D. Thesis (Applied Mechanics and Engineering Sciences), University of California, San Diego, 1993
- R2. Zhuang, Xuejin and Goddard, J.D. "Computer Simulation and Experiments on the QuasiStatic Mechanics and Transport Properties of Granular Media", Research Report GR 93-01 to the Air Force Office of Scientific Research on Grant AFOSR F49620-92-J-0037 (Project 2302, Task CS), for the period 10-01-92 to 09-30-93, University of California, San Diego, 1993.

---

\* Publications tangentially related to the present research and acknowledging partial AFOSR support

## Interactions

### Conference Presentations

T1. Goddard, J.D., "Quasi-Static Mechanics, Transport Properties and Statistical Physics of Granular Media" Joint European Science Foundation/U.S. National Science Foundation Workshop on Particulate and Multiphase Processes, Strasbourg, France, 15-16 June 1992.

T2. (3 talks) Goddard, J.D., "New ... Estimates for Reynolds Dilatancy in Granular Media" (Paper No. 2, Session "Theory 1") 11th International Congress on Rheology, Brussels, Belgium, 17-21 August, (Paper No. 769, Session BD5, Granular Materials and Rock Mechanics) 18th International Congress of Theoretical and Applied Mechanics, Haifa, Israel, 22-28 August, and (Paper No. 3, Session T-34) 29th Annual Technical Meeting, Society for Engineering Science, UCSD, La Jolla, CA, 14-16 September, 1992.

T3. Goddard, J.D., "A Kinematical Derivation of the Reynolds Yield Surface for Granular Media", 64th Annual Meeting, Society of Rheology, Santa Barbara, CA, 7-11 February 1993.

T4. (4 talks) "...Quasi-Static Mechanics and Transport Properties of Granular Assemblages", Paper S20, 65th Ann. Society of Rheology Mtg., Boston, MA, 17-21 Oct., Paper 199a, Ann. Mtg. A.I.Ch.E., St. Louis, MO, 7-12 Nov. 1993, AFOSR/UCSD IMM Workshop on the Mechanics and Statistical Physics of Particulate Materials, La Jolla, CA, 8-10 June, and Paper at 12th U.S. National Congress Appl. Mech., Seattle, WA, 27 June-1 July, 1994 (with X. Zhuang and A.K. Didwania)

T5. "On Strain-Jump Experiments and Rate-Type Models of Viscoelasticity," Paper G5, 65th Annual Society of Rheology Meeting, Boston, October 17-21, 1993.\*

T6. (videotape presentation) "Numerical Simulation of the Micromechanics of Granular Assemblages" by X. Zhuang and J.D. Goddard, Session "Rheology in Motion", 65th Ann. Society of Rheology Meeting, Boston, October 17-21, 1993

T7. "Generalized Taylor Dispersion and Brownian Dynamical Systems", Paper 138a, Ann. Mtg. A.I. Ch.E., St. Louis, MO, 7-12 November 1993\*

T8. "Taylor Dispersion for Dilettantes", Graduate Seminar, Caltech, Chem. Eng. 7 April, 1994\*

T9. "Rheology of Granular Materials - Life without  $kT$ ", Graduate Seminar, University of Wisconsin, Chem. Eng. and Rheology Research Ctr., Madison, WI, 3 May 1994

T10. "Material Instabilities and Spatial Patterns in Complex Fluids" (Plenary Lecture), 2nd NASA Microgravity Conference on Fluid Dynamics, Cleveland, OH, 17-21 June 1994.\*

T11. "Experiment and Numerical Simulation - Quasistatic Mechanics and Transport Properties of Granular Media" (two lectures), NATO Advanced Study Institute "Mobile Particulate Systems", Cargese, Corsica, 5-15 July 1994.

T12. "Yield Surfaces for Assemblages of Non-Cohesive Spheres" Paper F2, 66th Ann. Society of Rheology Meeting, Philadelphia, October 3-6, 1994. (with A.K. Didwania and X. Zhuang)

T13. (three talks) Goddard, J.D., "Yield Surfaces for Frictional Sphere Assemblages" (invited paper), Workshop: "Dynamics of Granular Materials", James Franck Institute, U. Chicago, 11-13 May, Joint Applied Mechanics and Materials Summer Meeting, ASME, UCLA, 28-30 June, and AFOSR Particulate Mechanics Contractor/Grantee Symposium, 22-23 September, 1995.

T14. Goddard, J.D., "A general theory of collisional impact and restitution in particulate systems", accepted for presentation in session Fundamental Research in Fluid Mechanics: Particulate and Multiphase Flows, Ann. AIChE meeting, Miami, 12-17 November 1995.\*

Consultative Advisory Functions and Professional Activities of P.L. J.D. Goddard

*Continuing:*

Editorial Board, J. Non-Newtonian Fluid Mech. (Elsevier), 1976-

American Institute of Chemical Engineers, National Fluid Mechanics Programming Committee, 1985-

U.S. Society of Rheology Representative to U.S. Committee on Theoretical and Applied Mechanics (US NCTAM) and Chair, U.S. Paper Screening Subcommittee for 18th ICTAM, 1992. U.S. Society of Rheology President, 1992-1993, Past President and Member of the Executive Committee, 1994-1995.

*Initiated during current AFOSR Grant activity:*

National Aeronautics and Space Administration, Discipline Working Group for Fluid Physics, 1992-

Chair, Session EC4, Biomechanics, 18th International Congress on Theoretical and Applied Mechanics (ICTAM), Haifa, Israel, 22-28 August 1992.

Session Chair, Suspensions (G), 11th International Congress on Rheology, Brussels, Belgium, 17-21 August 1992.

Editorial Board, Continuum Mechanics and Thermodynamics, Springer, 1992-1995

Technical Program Committee Member, 2nd International Conference on Discrete Element Methods, Sponsored by AFOSR, USBM and Intelligent Systems Laboratory, M.I.T., 18-19 March 1993.

Co-Organizer and Co-Chair (with J.T. Jenkins, Cornell, Martin Lewis, AFOSR, and S. Nemat-Nasser, UCSD), AFOSR/UCSD Institute for Mechanics and Materials workshop on particulate materials, La Jolla, CA, 8-10 June 1994.

Co-Organizer (with B.D. Coleman), workshop on material instabilities, Sacramento, CA, 7-8 October 1995 (Sponsored by the Society of Rheology, the National Science Foundation and the UCSD Institute for Mechanics and Materials).

American Physical Society, Division of Fluid Dynamics, 1996 Fluid Dynamics (ONR) Prize Committee, 1995.

Technical Program Committee and Session Chair, 67th Ann. Soc. of Rheology Meeting, Sacramento, CA, 8-12 October 1996

Session Co-Chair, Particulate and Multiphase Flows, Fundamental Research in Fluid Mechanics, Annual A.I.Ch.E. Mtg., Miami, 12-17 November 1995.

Technical Program Committee, 12th Internat. Congress Rheology, Quebec City, Canada, August 1996

Technical Program Committee, Powders and Grains 1997, Durham, NC, 18-21 May 1997.

Co-Organizer and Instructor (with J.T. Jenkins), short course for NASA personnel, "Mechanics of Granular Materials", Lewis Research Center, Cleveland, OH, 14-18 August, 1995.

Editorial Board, International Journal of Engineering Science (Elsevier), 1995-

**Honors/Awards**

J.D. Goddard, Invited Researcher, Isaac Newton Institute for Mathematical Sciences, Cambridge University, U.K., (Programme on Complex Fluids), January - June 1996